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Award Number: DAMD17-99-1-9361

TITLE: Selective DNA Delivery to Breast Cancer Cells

PRINCIPAL INVESTIGATOR: Stephen Dewhurst, Ph.D.

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REPORT DATE: June 2002

TYPE OF REPORT: Annual

PREPARED FOR: U.S. Army Medical Research and Materiel Command  
Fort Detrick, Maryland 21702-5012

DISTRIBUTION STATEMENT: Approved for Public Release;  
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20020913 044

# REPORT DOCUMENTATION PAGE

*Form Approved  
OMB No. 074-0188*

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED	
	June 2002	Annual (1 Jun 01 - 31 May 02)	
4. TITLE AND SUBTITLE			5. FUNDING NUMBERS
Selective DNA Delivery to Breast Cancer Cells			DAMD17-99-1-9361
6. AUTHOR(S) Stephen Dewhurst, Ph.D.			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)  University of Rochester Rochester, New York 14627			8. PERFORMING ORGANIZATION REPORT NUMBER
E-MAIL: <u>STEPHEN DEWHURST@URMC.ROCHESTER.EDU</u>			
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)  U.S. Army Medical Research and Materiel Command Fort Detrick, Maryland 21702-5012			10. SPONSORING / MONITORING AGENCY REPORT NUMBER
11. SUPPLEMENTARY NOTES			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for Public Release; Distribution Unlimited			12b. DISTRIBUTION CODE
13. ABSTRACT <i>(Maximum 200 Words)</i>			
<p>The hypothesis of this research is that specific cell-binding proteins or peptides can be used to enhance (therapeutic) DNA delivery to breast carcinomas; this hypothesis is being experimentally tested.</p> <p>During the period covered by this progress report, we have continued our analyses of the novel <math>\alpha\beta 3</math>-binding proteins which we first described in our previous annual report. These were developed by the directed mutagenesis of a natural integrin-binding protein, the tenth fibronectin type III domain (FNfn10), and subsequent screening of a library of these molecules, using phage display technology. A novel derivative of FNfn10 was identified and shown to bind with high affinity and specificity to purified <math>\alpha\beta 3</math> integrin. It also interacted with cell surface-expressed <math>\alpha\beta 3</math>, as determined by flow cytometry, but did not bind detectably to other cell surface integrins.</p> <p><b>Overall</b>, these experiments have provided important tools and insights that will enhance gene transfer to breast carcinomas.</p>			
14. SUBJECT TERMS Breast Cancer; her2; adenovirus; phage display; gene transfer			15. NUMBER OF PAGES 55
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited

FOREWORD

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X For the protection of human subjects, the investigator(s) adhered to policies of applicable Federal Law 45 CFR 46.

  In conducting research utilizing recombinant DNA technology, the investigator(s) adhered to current guidelines promulgated by the National Institutes of Health.

  In the conduct of research utilizing recombinant DNA, the investigator(s) adhered to the NIH Guidelines for Research Involving Recombinant DNA Molecules.

  In the conduct of research involving hazardous organisms, the investigator(s) adhered to the CDC-NIH Guide for Biosafety in Microbiological and Biomedical Laboratories.

  
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PI - Signature

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Date

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## INTRODUCTION

A number of gene delivery systems, including virally-based vectors as well as non-viral methods, are presently being explored as potential DNA delivery vehicles for gene- and immunotherapy of breast cancer. However, currently available DNA delivery vehicles for gene therapy of breast cancer have a very wide host cell range, making it difficult to specifically target them to tumor cells. Therefore, the experiments that were performed under the auspices of this grant award were aimed at developing innovative new approaches that will allow one to selectively target DNA molecules to breast cancer cells. The underlying hypothesis which we explored was as follows: that one can use specific protein or peptide sequences to selectively target linked DNA molecules to breast cancer cells. This hypothesis was explored by a combination of approaches, including the use of peptide phage display libraries and recombinant adenovirus-derived gene delivery systems.

## BODY

### Approved Tasks

The following tasks were outlined in the approved statement of work for this grant:

- *Task 1. Analysis of DNA delivery by adenovirus penton base proteins (AdPB) (months 1 - 12)*
- *Task 2. Application of phage display technology to the identification of breast cancer targeting peptides (months 1 - 15). Timeline extended to 1-36 months.*
- *Task 3. Analysis of DNA delivery to breast cancer cells by novel peptides (months 16-30). Timeline extended to 16-36 months.*
- *Task 4. Studies of DNA delivery using an *in vivo* xenograft model for breast cancer (months 25-36). Originally included in the approved tasks, but ultimately deferred until a future date, when more compelling *in vitro* data exist. The adenovirus penton base proteins developed in Aim 1 did not show sufficient promise to merit performance of these *in vivo* studies. This decision was made for two major reasons. First, the AdPB proteins mediated DNA delivery with a lower level of efficiency than commercially available reagents such as lipofectamine. Second, DNA delivery by AdPB required the formation of unstable trimolecular complexes, incorporating AdPB, DNA and a bridging peptide. It was deemed highly unlikely that a trimolecular complex of this kind, held together by low-affinity peptide-DNA and peptide-protein interactions would remain intact *in vivo*. We therefore decided to extend Task 2, because we obtained exciting preliminary data in these experiments. In particular, we focussed our attention on the derivation of more promising lead molecules, with the ability to interact with key cell surface receptors expressed on breast cancers (*i.e.*,  $\alpha\beta\gamma$  integrin and CD40; see below).*

Research Accomplishments associated with the above tasks

**Task 1:** Experiments on the analysis of DNA delivery by adenovirus penton base proteins were reported in a previous annual report. We have not performed any work with these materials during the period covered by the present report.

**Task 2:** Experiments aimed at the identification of novel breast cancer targeting peptides generated results that included the following, previously unreported, findings:

- We conducted directed mutagenesis of a natural integrin-binding protein, the tenth fibronectin type III domain (FNfn10), and subsequent screening of a library of these molecules, using phage display technology. A novel derivative of FNfn10 was identified and shown to bind with high affinity and specificity to purified  $\alpha v\beta 3$  integrin. It also interacted with cell surface-expressed  $\alpha v\beta 3$ , as determined by flow cytometry, but did not bind detectably to other cell surface integrins. These results are summarized below and in greater detail in the manuscript by Richards and coworkers (see Appendix; *Richards J., et al. A fibronectin type III domain modified with a novel RGDWXE consensus sequence binds with enhanced affinity and specificity to human  $\alpha v\beta 3$  integrin. Submitted for publication*).

## Background: Why Target $\alpha v\beta 3$ ?

Alphavbeta3 (CD51/CD61) is a member of the integrin family of cell surface adhesion receptors. Over 20 different  $\alpha\beta$  integrin heterodimers exist, each with different tissue and ligand specificities. Normal tissue distribution of  $\alpha v\beta 3$  is generally limited to high levels of expression on osteoclasts, with lower levels observed on platelets, megakaryocytes, kidney, vascular smooth muscle, placenta, dendritic cells, and in varying amounts on normal endothelium.

$\alpha v\beta 3$  integrin is a multifunctional cell surface receptor that has pleiotropic roles in normal cell growth and survival, and which can contribute to oncogenesis. Consistent with this, upregulation of  $\alpha v\beta 3$  expression has been observed on the endothelial cells of angiogenic vessels, and binding of  $\alpha v\beta 3$  to the basement membrane is a critical step in the angiogenesis induced by basic fibroblast growth factor and tumor necrosis factor alpha (5). Expression of  $\alpha v\beta 3$  has also been implicated in tumor invasion, and it has been shown that  $\alpha v\beta 3$  binds matrix metalloproteinase-2 (MMP-2) and presents MMP-2 on the surface of invasive carcinomas and on invasive angiogenic endothelial cells (2, 7).

$\alpha v\beta 3$  also regulates cell growth and survival, since ligation of this receptor can, under some circumstances, induce apoptosis in tumor cells (6). Furthermore, disruption of cell adhesion with anti- $\alpha v\beta 3$  antibodies, RGD peptides, and other integrin antagonists has been shown to slow tumor growth (1, 3, 4). Finally, the selective upregulation of  $\alpha v\beta 3$  expression on tumor blood vessels is also being explored as the basis for imaging of neoplastic lesions, and the  $\alpha v\beta 3$ -specific antibody LM609 has been successfully used for this purpose *in vivo* (8).

Novel molecules capable of binding with high specificity to  $\alpha v\beta 3$  integrin have potential utility in several applications, and as a consequence,  $\alpha v\beta 3$  is an important target for drug discovery and selection of new binding ligands. The tenth fibronectin type III domain (FNfn10) was developed as a phage display scaffold because of its small size (94 residues), monomeric assembly, and ability to retain its folded  $\beta$ -sheet morphology while exposed loops were randomized. In addition, FNfn10 lacks cysteine residues and requires no post-translational modification, allowing for large-scale bacterial expression. We reasoned that since FNfn10 binds  $\alpha v\beta 3$  *in vivo*, affinity maturation of the RGD sequence in the exposed FG loop might result in a modified FNfn10 with high-affinity for  $\alpha v\beta 3$ . We further reasoned that a modified derivative of FNfn10 might be particularly useful for vector or gene delivery applications because of (1) the small size of this protein, (2) its simple monomeric structure, and (3) its lack of disulfide bonds. These considerations suggested to us that it ought to be possible to place a modified FNfn10 on the surface of bacteriophage or virus vectors (for DNA delivery applications) and also to derivatize the protein in such a way as to link it directly to plasmid DNA molecules. As such, the modified FNfn10 protein might be expected to have major advantages over the adenovirus penton base protein (AdPB), which emerged as a somewhat more difficult reagent, due in part to its larger size, disulfide bonds and propensity to form multimers.

## Summary of findings

As noted above, we have utilized a natural integrin-binding protein, the tenth fibronectin type III domain (FNfn10), as a scaffold for the selection of novel  $\alpha v\beta 3$ -binding molecules. By randomizing residues surrounding the RGD sequence in the flexible FG loop of FNfn10, we selected  $\alpha v\beta 3$ -binding modified FNfn10 clones with a novel RGDWXE consensus sequence. One of these clones, 3JCL14-FNfn10, binds with high affinity and specificity to purified  $\alpha v\beta 3$  integrin. It also interacts with cell surface-expressed  $\alpha v\beta 3$ , as determined by flow cytometry, but does not bind detectably to other cell surface integrins. Taken together, these data show that 3JCL14-FNfn10 is

a specific, high-affinity  $\alpha v\beta 3$ -binding protein which may have utility in future applications involving the targeting of  $\alpha v\beta 3$ -positive cells.

**The complete results from this work are included in the Appendix, in the manuscript by Richards et al.**

## **KEY RESEARCH ACCOMPLISHMENTS OF DURING THIS PERIOD**

- ❖ Utilization of a natural integrin-binding protein, the tenth fibronectin type III domain (FNfn10), as a scaffold for the selection of novel  $\alpha v\beta 3$ -binding molecules and successful identification of novel integrin-binding proteins using this method. Briefly, by randomizing residues surrounding the RGD sequence in the flexible FG loop of FNfn10, we selected  $\alpha v\beta 3$ -binding modified FNfn10 clones with a novel RGDWXE consensus sequence. One of these clones, 3JCLI4-FNfn10, binds with high affinity and specificity to purified  $\alpha v\beta 3$  integrin. It also interacts with cell surface-expressed  $\alpha v\beta 3$ , as determined by flow cytometry, but does not bind detectably to other cell surface integrins. Taken together, these data show that 3JCLI4-FNfn10 is a specific, high-affinity  $\alpha v\beta 3$ -binding protein. These properties, combined with the small, monomeric, cysteine-free and highly stable structure of 3JCLI4-FNfn10, may make this protein useful in future applications involving the targeting of  $\alpha v\beta 3$ -positive cells.

## **REPORTABLE OUTCOMES**

**Manuscripts, abstracts, presentations:** See Bibliography

**Patents and licenses applied for and/or issued:** None

**Degrees obtained that are supported by this award:** None

**Development of cell lines, tissue or serum repositories:** None

**Informatics such as databases and animal models, etc:** None

**Funding applied for based on work supported by this award:** None

**Employment or research opportunities applied for and/or received on experiences/training supported by this award:** Research training was provided for Ms. Michelle Miller was provided (Ms. Miller is a 1999 college graduate, who has been working on this project as a laboratory technician). It is expected that Ms. Miller will attend graduate school within the next 1-2 years, to obtain her Ph.D. (personal communication from Ms. Miller), and the present research experiences should assist her in that goal. Research training for two summer undergraduate researchers, Ms. Johanna Abend and Ms. Laura McLane, was also provided. Ms. Abend's long-term goals include graduate (Ph.D.) education — a goal which will be enhanced by her training under this award. Ms. McLane's long-term goals are similar, although she is presently employed as a laboratory technician at Emory University.

## **CONCLUSIONS**

The conclusions which can be drawn from this period of research are as follows:

- ❖ A natural integrin-binding protein, the tenth fibronectin type III domain (FNfn10), can be successfully used as a scaffold for the selection of novel  $\alpha\beta 3$ -binding molecules. By randomizing residues surrounding the RGD sequence in the flexible FG loop of FNfn10, we selected  $\alpha\beta 3$ -binding modified FNfn10 clones with a novel RGDWXE consensus sequence. One of these clones, 3JCLI4-FNfn10, was shown to bind with high affinity and specificity to purified  $\alpha\beta 3$  integrin. It also interacted with cell surface-expressed  $\alpha\beta 3$ , as determined by flow cytometry, but did not bind detectably to other cell surface integrins. Thus, we were able to derive a novel, specific, high-affinity  $\alpha\beta 3$ -binding protein. This protein is small, monomeric, cysteine-free and highly stable, which may make it very useful in future applications involving the targeting or detection of  $\alpha\beta 3$ -positive cells (such as those found in breast tumor vasculature).

### **So What Section**

The knowledge gained from these experiments advances the basic goals proposed in the original grant application, and provides important tools and insights into approaches which can be used to selectively deliver therapeutic DNA to breast cancers.

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**BIBLIOGRAPHY (PUBLICATIONS)**  
*These materials are all also included as Appendices*

**Manuscripts:**

J. Richards, M. Miller, A. Koide, S. Koide, S. Dewhurst. A fibronectin type III domain modified with a novel RGDWXE consensus sequence binds with enhanced affinity and specificity to human  $\alpha_v\beta_3$  integrin. Submitted for publication in the Journal of Biological Chemistry, 2002.

**Abstracts:**

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## **LIST OF PERSONNEL**

*List of personnel who were supported from the research effort during this period*

<b>Individual</b>	<b>Role</b>
Stephen Dewhurst, PhD	PI
John Frelinger, Ph.D.	CoPI
Michelle Miller, B.S.	Technician
Johanna Abend, B.S.	Summer undergraduate researcher

## **APPENDIX MATERIALS**

Award Number: DAMD17-99-1-9361

TITLE: Selective DNA Delivery to Breast Cancer Cells

PRINCIPAL INVESTIGATOR: Stephen Dewhurst, Ph.D.

CONTRACTING ORGANIZATION: University of Rochester Medical Center  
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TYPE OF REPORT: Annual

### **List of Materials Appended**

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¥ 1 page

## ABSTRACT

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To improve the safety and efficacy of viral vectors in vaccine and gene therapy studies, it is advantageous to exercise control over the target cell tropism of the vectors. Since phage display technology allows for the selection of receptor-specific ligands, this technique has been adapted to screening for ligands to alpha<sub>v</sub>beta<sub>3</sub> integrin. Our goal is to find both high-affinity binding ligands as well as ligands which will trigger receptor internalization. The cell adhesion receptor alpha<sub>v</sub>beta<sub>3</sub> ( $\alpha_v\beta_3$ ) integrin is a target of interest because of its expression on endothelial, dendritic, and cancer cells; its role in angiogenesis; and its involvement in the entry of many viruses (including adenovirus) into host cells. Previous work using phage display methods has resulted in the identification of short  $\alpha_v\beta_3$ -binding peptides containing the RGD consensus motif. However, we believe that it may be possible to select for higher affinity interactions using a small protein scaffold. Fibronectin is a natural ligand for  $\alpha_v\beta_3$ , which is comprised of multiple domains. The tenth fibronectin type III domain (FN3) of human fibronectin is a very stable, small (< 100 amino acids), structurally defined molecule with an immunoglobulin-like structure and a loop containing the RGD sequence. We have established phage display systems for FN3 [Koide et al. (1998) J. Mol. Biol. 284:1141]. By randomizing the residues in the FG loop of FN3 in a library displayed on M13 bacteriophage, sequences binding with much higher affinity to  $\alpha_v\beta_3$  were selected, all of which contain a consensus sequence. This FN3 library has also been screened for internalization into selected cell lines of interest. Future applications may include not only gene therapy/vector development but also tumor inhibition and tumor detection/visualization.

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**A fibronectin type III domain modified with a novel RGDWXE consensus sequence binds  
with enhanced affinity and specificity to human  $\alpha v\beta 3$  integrin**

Julie Richards<sup>§</sup>, Michelle Miller<sup>§</sup>, Akiko Koide<sup>¶</sup>, Shohei Koide<sup>¶</sup>, Stephen Dewhurst<sup>§\*</sup>

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Running Title: Fibronectin type III domain with enhanced binding to  $\alpha v\beta 3$

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<sup>+</sup> This work was supported by Department of Defense (DOD) grants to S.D. and S.K. (DAMD17-99-1-9361, DAMD17-01-1-0384, DAMD17-01-1-0385), and by NIH grant R29-GM55042 to S.K..

Julie Richards is a trainee in the Medical Scientist Training Program funded by NIH grant T32 GM07356 and by T32 AI07362 (J.R.) The U.S. Army Medical Research Acquistion Activity, 820 Chandler Street, Fort Detrick MD 21702-5014 is the awarding and administering acquistion office. This article does not necessarily reflect the position of the Government, and no official endorsement should be inferred.

## Fibronectin type III domain with enhanced binding to $\alpha v\beta 3$

### Summary

Alphavbeta3 integrin is a cell surface receptor involved in normal cell growth, attachment, and migration; it has also been implicated in tumor invasion and angiogenesis and is of considerable interest as a target for therapeutics and gene delivery. In the present work, we have utilized a natural integrin-binding protein, the tenth fibronectin type III domain (FNfn10), as a phage display scaffold for the selection of novel  $\alpha v\beta 3$ -binding molecules. By randomizing residues surrounding the RGD sequence in the flexible FG loop of FNfn10, we selected  $\alpha v\beta 3$ -binding modified FNfn10 clones with a novel RGDWXE consensus sequence. One of these clones, 3JCLI4-FNfn10, binds with high affinity and specificity to purified  $\alpha v\beta 3$  integrin. It also interacts with cell surface-expressed  $\alpha v\beta 3$ , as determined by flow cytometry, but does not bind detectably to other cell surface integrins. In contrast to the disintegrin echistatin, which inhibits both  $\alpha v\beta 3$ - and  $\alpha IIb\beta 3$ -mediated cell adhesion, 3JCLI4-FNfn10 inhibits only  $\alpha v\beta 3$ -specific attachment. Taken together, these data show that 3JCLI4-FNfn10 is a specific, high-affinity  $\alpha v\beta 3$ -binding protein that can inhibit  $\alpha v\beta 3$ -dependent cellular processes. These properties, combined with the small, monomeric, cysteine-free and highly stable structure of 3JCLI4-FNfn10, may make this protein useful in future applications involving detection and targeting of  $\alpha v\beta 3$ -positive cells.

## Fibronectin type III domain with enhanced binding to $\alpha v\beta 3$

### Introduction

Alphavbeta3 (CD51/CD61) is a member of the integrin family of cell surface adhesion receptors. Over 20 different  $\alpha\beta$  integrin heterodimers exist, each with different tissue and ligand specificities. Normal tissue distribution of  $\alpha v\beta 3$  is generally limited to high levels of expression on osteoclasts, but is also observed on platelets, megakaryocytes, kidney, vascular smooth muscle, placenta, dendritic cells(1), and in varying amounts on normal endothelium (reviewed in (2)). In contrast to  $\alpha 5\beta 1$ , which binds to only fibronectin,  $\alpha v\beta 3$  binds to a wide range of RGD-containing integrin ligands, including but not limited to fibronectin, vitronectin, osteopontin, von Willebrandt factor, and fibrinogen(2).

$\alpha v\beta 3$  integrin is a multifunctional cell surface receptor that has pleiotropic roles in normal cell growth and survival, and which can contribute to oncogenesis. Consistent with this, upregulation of  $\alpha v\beta 3$  expression has been observed on the endothelial cells of angiogenic vessels, and binding of  $\alpha v\beta 3$  to the basement membrane is a critical step in the angiogenesis induced by basic fibroblast growth factor and tumor necrosis factor alpha(3). Expression of  $\alpha v\beta 3$  has also been implicated in tumor invasion, and it has been shown that  $\alpha v\beta 3$  binds matrix metalloproteinase-2 (MMP-2) and presents MMP-2 on the surface of invasive carcinomas and on invasive angiogenic endothelial cells(4,5).

$\alpha v\beta 3$  also regulates cell growth and survival, since ligation of this receptor can, under some circumstances, induce apoptosis in tumor cells(6). Furthermore, disruption of cell adhesion with anti- $\alpha v\beta 3$  antibodies, RGD peptides, and other integrin antagonists has been shown to slow tumor growth(7-9). Finally, the selective upregulation of  $\alpha v\beta 3$  expression on tumor blood vessels is also being explored as the basis for imaging of neoplastic lesions, and the  $\alpha v\beta 3$ -specific antibody LM609 has been successfully used for this purpose *in vivo*(10)

### Fibronectin type III domain with enhanced binding to $\alpha v\beta 3$

Novel molecules capable of binding with high specificity to  $\alpha v\beta 3$  integrin have potential utility in several applications, and as a consequence,  $\alpha v\beta 3$  has been a frequent target for drug discovery and selection of new binding ligands. Phage display technology, in which combinatorial peptide libraries are expressed on the surface of bacteriophage, has been used to select for peptide ligands capable of binding to  $\alpha v\beta 3$  -- yielding a wide range of RGD-containing peptide sequences capable of interacting at moderate affinity with  $\alpha v\beta 3$  and other integrins(11,12). Phage-displayed random peptide libraries have also been constructed and screened using framework proteins such as the cytotoxic T lymphocyte-associated antigen 4 (CTLA-4). This resulted in the identification of phage clones which could be used to stain human umbilical vein endothelial cells in a flow cytometric assay. However, the ability of the purified recombinant CTLA-4 protein to stain cells and its cross-reactivity with other integrins was not reported(13).

Fibronectin is a natural ligand of integrins, and it consists of repeats of three types of domains. The tenth fibronectin type III domain (FNfn10) contains the RGD sequence in the highly flexible loop connecting the F and G  $\beta$ -strands (FG loop) (14,15). FNfn10 was developed as a scaffold for phage display of peptides because of its small size (94 residues), monomeric assembly, and ability to retain its global fold while exposed loops were randomized(16). In addition, FNfn10 lacks cysteine residues and requires no post-translational modification, allowing for large-scale bacterial expression. We reasoned that since FNfn10 binds  $\alpha v\beta 3$  *in vivo* via the RGD sequence, modification of amino acid residues surrounding the RGD sequence in the FG loop might result in a modified FNfn10 with higher affinity and/or specificity for  $\alpha v\beta 3$ . In this study, we demonstrate that derivatives of FNfn10 with high affinity and specificity for  $\alpha v\beta 3$  can be selected from a partially randomized FNfn10 M13 phage library, expressed on the surface of phage M13. All  $\alpha v\beta 3$ -binding FNfn10 clones were found to contain a RGDWXE

Fibronectin type III domain with enhanced binding to  $\alpha v\beta 3$

consensus sequence, and the purified monomeric FNfn10-derived proteins were found to have similar characteristics to  $\alpha v\beta 3$ -specific monoclonal antibodies, with respect to their stability, specificity, affinity, and effects on cell adhesion.

## Fibronectin type III domain with enhanced binding to $\alpha v\beta 3$

### Experimental Procedures

*General reagents*--- All chemicals, unless otherwise specified, were obtained from Sigma (St. Louis, MO). Purified integrins, cell adhesion strips, and LM609 were purchased from Chemicon (Temecula, California). Echistatin and GRGDSPK peptide were obtained from Bachem (Torrence, California).

*Cell Culture*--- K562, K562- $\alpha v\beta 3$ , K562- $\alpha IIb\beta 3$ , K562- $\alpha v\beta 5$ , K562- $\alpha 4\beta 1$ , and K562- $\alpha 4\beta 7$  cells were a gift of Dr. S. Blystone (Upstate Medical University, Syracuse, NY)(17). K562 cells were maintained in Iscove's Modified Dulbecco's Medium (IMDM) (Gibco, Invitrogen, Grand Island, NY) supplemented with 10% fetal bovine serum (Sigma), 0.5U/L penicillin-streptomycin, and 2mM L-Glutamine (Gibco). K562- $\alpha v\beta 3$ , K562- $\alpha IIb\beta 3$ , K562- $\alpha v\beta 5$ , K562- $\alpha 4\beta 1$ , and K562- $\alpha 4\beta 7$  cells were maintained in the same media containing 500  $\mu$ g/ml G418 (GENETICIN) (Gibco).

*Construction of phage vectors*---We constructed a phage-display vector for FNfn10, JCFN, by cloning the FNfn10 gene(16) in the modified M13 vector, JC-M13-88(18). The FNfn10 gene was amplified from pAS38 (16) using oligonucleotides FN3JCM8Nhe (CCTAGCTAGCGTAGCTCAGGCCATGCAGGTTCTGATGTTC) and FN3JCM8Hin (GGCCAAGCTTGACCGCCACCAGAACCGCCACCGGTACGGTAG), digested with the restriction enzymes NheI and HindIII, and subcloned in JC-M13-88 using the same restriction enzyme sites so that the FNfn10 gene is placed in-frame between the OmpA signal sequence and M13 geneVIII. We confirmed that the JCFN phages prepared using *E. coli* XL-1blue displayed FNfn10 on the phage surface by ELISA (data not shown). Purified FNfn10 clones were expressed with an N-terminal histag and a C-terminal GKKKGK tag. The GKKKGK tag was incorporated to increase the solubility (16) and to serve as a preferred biotinylation site. FNfn10 genes were amplified using oligonucleotides FN1F2 (CGGGATCCCATATGCAGGTTCTGATGTTCCGCGTGACCTGGAAGTTGTTGCTGCGACC) and FN3GKKKGK (CCGACTCGAGTTACTATTTACCTTTTACCGGTACGGTAGTTAACGAG), digested

### Fibronectin type III domain with enhanced binding to $\alpha v\beta 3$

with the restriction enzymes NdeI and XhoI, and ligated with pAS45 (16) digested with the same restriction enzymes. The expression vector for the wild type protein, pAS54, contained an Arg6 to Thr mutation that had been introduced to remove a secondary Thrombin site (16).

*Construction of the FNfn10 library*--We constructed a FNfn10 library, JCFN-RGD, in such a way that the FG loop has XRGDXXXX sequence where X stands for any amino acids (residue #77-84; residue numbering is according to Figure 2(a) of Koide et al. (1998) (16)). Mutagenesis on the JCFN template was performed according to Kunkel's method(19) using an oligonucleotide JCFNFGRGD (GTTAACATCGAGATTGGCTTGGAMNNMNNMNNATGCCGCGMNNAGTAACAGCGTATAC, where N is a mixture of A, G, C and T, and M is a mixture of A and C). *E. coli* SS320 was electro-transformed with the mutagenesis mixture, resulting in a phage library containing  $1.5 \times 10^9$  independent clones. The phages were re-amplified in *E. coli* XL1-blue with various concentrations of isopropyl  $\beta$ -D-thiogalactopyranoside (IPTG).

*$\alpha v\beta 3$  biopanning using the JCFN-RGD library*-- Integrin biopanning was performed similarly to the method previously described(11). Purified  $\alpha v\beta 3$  (5 $\mu$ g/ml in TBS buffer containing 2 mM CaCl<sub>2</sub>) was bound to a single microtiter well of a 96-well plate. The well was rinsed 3 times with sterile water containing 2 mM CaCl<sub>2</sub> and blocked with 5% phage blocking reagent (Novagen, Darmstadt, Germany) for one hour at room temperature. The plate was rinsed 5 times with TBS buffer containing 0.1% Tween-20 and 2 mM CaCl<sub>2</sub>, then incubated with JCFN-RGD library diluted in 5% blocking reagent for one hour. The plate was washed ten times with TBS buffer containing 0.1% Tween 20 and 2 mM CaCl<sub>2</sub> and bound phage were eluted with 0.2 M glycine-HCl (pH 2.2) containing 1 mg/ml BSA for 10 minutes at room temperature with gentle agitation and neutralized with 15% (v/v) of 1 M Tris-HCl (pH 9.1). The phage were amplified using the *E. coli* ER2738 host strain (New England Biolabs, Beverly, MA) in the presence of 1mM, 0.1 mM or with no IPTG and purified by precipitating with 20 % (w/v) polyethylene glycol-8000, 2.5 M NaCl and resuspending in PBS containing 20 % (v/v) glycerol. The biopanning and amplification of

### Fibronectin type III domain with enhanced binding to $\alpha v\beta 3$

eluted phage were repeated for two more rounds. Upon completion of three rounds of biopanning, individual phage clones were amplified and the genomes were purified by phenol extraction. Polymerase chain reaction was performed with the primers SFN3F  
(AGCTCAATTGGTCCGGTGGAGGTTCTGATGTTCCCGCGTGACCTG) and SFN3R  
(AGCTAAGCTTTAGGTACGGTAGTTAACGAGAT) to amplify the FNfn10 domain. The DNA was sequenced using the SFN3F primer.

*Protein preparation*--The expression of FNfn10 proteins was performed as previously described (16) except that the proteins were further biotinylated. After biotinylation, the protein-containing solution was applied to a nickel affinity column and unbound materials were washed off; the column was then equilibrated with 50mM sodium phosphate buffer (pH8.0) containing 500mM sodium chloride. D-biotinoyl- $\epsilon$ -aminocaproic acid N-hydroxysuccinimide ester (726 $\mu$ M) (Boehringer Mannheim, Mannheim, Germany) in the same buffer was applied to the column, and the column was incubated for an hour at room temperature to perform biotinylation. This biotinylation process was performed a total of three times. Then the column was washed with 20mM Tris-HCl buffer (pH8.0) containing 500mM sodium chloride, and the biotinylated FNfn10 was eluted with the buffer containing 500mM imidazole. The proteins purified in this manner were >90% pure as judged by SDS-PAGE and reverse phase chromatography. Protein concentrations for subsequent analyses were determined by Bradford assay and confirmed by SDS-PAGE analysis and Coomassie Brilliant Blue staining. Biotinylation was confirmed by Western analysis with streptavidin-horseradish peroxidase (Oncogene, Cambridge, MA).

*ELISA detection of biotinylated FNfn10 clones*-- Purified integrin was bound to a flat-bottom, high-binding EIA/RIA plate (Corning Costar, Corning, NY) at a concentration of 5  $\mu$ g/ml in TBS for 12-16 hours at 4 °C. The plate was washed once with TBS and blocked for 2 hours at room temperature with 0.1M NaHCO<sub>3</sub>, 0.5 mg/ml BSA, 0.2% NaN<sub>3</sub>, pH 8.6. Biotinylated FNfn10 clones were bound in TBST+ Ca<sup>++</sup> (TBS 0.1% Tween-20, 2mM CaCl<sub>2</sub>). Plates were washed ten times with TBST+ Ca<sup>++</sup> and incubated 20 minutes with 2  $\mu$ g/ml streptavidin-horseradish peroxidase (Oncogene) in TBST+ Ca<sup>++</sup> at room temperature. Plates were

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washed ten times with TBST+ Ca<sup>++</sup>. Bound peroxidase was detected with ABTS (2,2'-azino-di-3-ethylbenzthiazoline sulfonic acid) peroxidase substrate (Sigma), 1 mg/ml in 0.1 M NaCitrate, 0.1 M Na<sub>2</sub>HPO<sub>4</sub>, pH 4.0 supplemented with 0.03% hydrogen peroxide. Color was allowed to develop for 10-15 minutes and the A<sub>400</sub> was read with a SpectraCount ELISA reader (Packard, Downers Grove, IL).

*Flow cytometric detection of cell-binding by biotinylated FNfn10 and FNfn10-3JCLI4-- K562 cells (10<sup>5</sup>) transfected with various integrins were resuspended in 5 ml FACS buffer (PBS, 0.5% BSA, 0.1% NaN<sub>3</sub>), washed, and resuspended in FACS buffer containing either 0.4  $\mu$ g/ml FNfn10 protein (wild-type of 3JCLI4) or 1  $\mu$ g/ml LM609 , prior to incubation at room temperature for 20 minutes. Cells were then washed with 5 ml FACS buffer, incubated in 1:50 streptavidin-APC (BD Pharmingen, San Diego, California) for 20 minutes and washed again with 5 ml FACS buffer, prior to detection of cell surface fluorescence using a FACSCalibur flow cytometer (Becton Dickinson, San Jose, California).*

*Cell adhesion assays--- Fibronectin and vitronectin-coated strips (Chemicon) were rehydrated 15 minutes in PBS. Inhibitor in IMDM/10% FBS was added to the bottom of the well, and 10<sup>5</sup> cells/well in maintenance media were added to a final volume of 100  $\mu$ l/ well. Cells were incubated 2 hrs at 37°C, 5% CO<sub>2</sub>, washed three times with PBS at room temperature, and stained 10 minutes with 0.2% crystal violet, 10% ethanol. Cells were then washed three times with PBS and solubilized with a 1:1 ratio of PBS:absolute ethanol for 10 minutes with agitation. A<sub>600</sub> was measured using a SpectraCount ELISA reader (Packard).*

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### Results

*Screening of the JCFN-RGD phage display library for  $\alpha v\beta 3$  binding resulted in selection of phage clones containing an RGDWXE in the FG loop of displayed FNfn10.* In the FNfn10 structure the FG loop corresponds to residues 78-87, and the RGD sequence to residues 79-81 (residue numbering according to the Protein Data Bank entry 1TTG(14)). The five residues immediately adjacent to the RGD sequence in the FG loop were modified. The JCFN-RGD (XRGDXXXX) library contained approximately  $1.5 \times 10^9$  independent clones, sufficiently large to include all possible sequences. The library was amplified in 0.0, 0.1, or 1.0 mM IPTG to vary FNfn10 copy number and screened for binding to  $\alpha v\beta 3$  integrin. After 3 rounds of biopanning, 100-1000 fold increased recovery of phage was observed compared to the initial library (data not shown). Of 20 phage clones sequenced, 8 contained an RGDWXE consensus sequence (Figure 1a). Phage inputs of  $10^9$ ,  $10^8$ , or  $10^7$  pfu were then allowed to bind to  $\alpha v\beta 3$  or BSA coated wells and bound phages were recovered with 0.2M glycine, pH2.2. Using phage clones amplified in 1 mM IPTG (high FNfn10 copy number), phage clones containing the RGDWXE consensus were recovered at levels of 0.01-1% input from  $\alpha v\beta 3$  coated wells; the clones were recovered at approximately 1000-fold lower levels from BSA coated wells and integrin-binding was found to be calcium-dependent (not shown). In contrast, clones which lacked the RGDWXE motif were recovered at equivalent levels from both  $\alpha v\beta 3$  coated and BSA coated wells (data not shown).

The RGDWXE-containing clones were amplified in the absence of IPTG so as to decrease the expressed copy number of FNfn10 protein on the phage surface, and the panel of clones were then directly compared in a phage binding assay, for their ability to bind to  $\alpha v\beta 3$  (Figure 1b). The clones recovered at the highest level were 2JCAV1, 2JCAV2, 3JCAV3, 3JCNI1, and

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3JCLI4, all of which were recovered at a level of approximately 0.1% of input phage from  $\alpha v\beta 3$ -coated wells and at 1000-fold lower levels from BSA-coated wells. Therefore, varying FNfn10 copy number on M13 by IPTG concentration did not have an effect on the relative binding efficiency of the clones isolated, suggesting that the binding interaction between the  $\alpha v\beta 3$  integrin and the phage-displayed FNfn10 derivatives might be of high affinity.

The modified FNfn10 proteins expressed by this panel of phage clones were expressed as an isolated protein in *E.coli*, purified and biotinylated. 3JCLI4 (the second-highest recovered clone in phage binding assays), was selected for further study because the purified FNfn10 protein derived from clone 2JCAV1 (the highest recovered clone) proved to be rather insoluble and prone to precipitation. SDS polyacrylamide gel electrophoresis and Coomassie blue staining revealed the presence of a single protein of the expected size (~15 kDa) within the purified preparation of biotinylated FNfn10-3JCLI4 protein. Western blot analysis using a monoclonal antibody specific for the hexahistidine epitope tag on the purified FNfn10 protein confirmed the identity of this protein (not shown), and further analysis revealed that (as expected) the binding of both the phage clone 3JCLI4 and of the corresponding purified protein (FNfn10-3JCLI4) to  $\alpha v\beta 3$  integrin was  $Ca^{++}$  dependent and could be eliminated in the presence of EDTA (data not shown).

*FNfn10-3JCLI4 displays high affinity and specificity for plate-immobilized  $\alpha v\beta 3$ .* Biotinylated FNfn10-3JCLI4 and biotinylated wild-type FNfn10 (FNfn10-WT) were allowed to bind to  $\alpha v\beta 3$ ,  $\alpha 1\beta 1$ , or BSA coated wells in approximate half-log increments from 0.0001 to 0.1  $\mu g/ml$ , corresponding to molar concentrations of 8 pM to 8 nM. Bound biotinylated protein was detected by ELISA (Figure 2a). Assuming a high ratio of free to bound FNfn10-3JCLI4, the equation  $y=m1*x / (m2 + x)$  was fit to the data ( $R>0.99$ ) to determine the half-maximal binding affinity of

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0.01  $\mu$ g/ml or 800 pM. At each concentration examined, the binding of biotinylated FNfn10-3JCLI4 to  $\alpha v\beta 3$  was higher than that for FNfn10-WT, and 3JCLI4 was not found to bind detectably to the  $\alpha 1\beta 1$  integrin (i.e., binding to  $\alpha 1\beta 1$  was identical to binding to BSA).

We next examined the kinetics of protein association and dissociation. After allowing biotinylated FNfn10-3JCLI4 to bind to  $\alpha v\beta 3$ -coated wells, 100 fold excess unlabelled FNfn10-3JCLI4 was added to some wells and the plates were incubated for a further 24 hours; control wells were incubated in the absence of the unlabelled competitor. At the end of this time, the amount of plate-bound biotinylated FNfn10-3JCLI4 was assessed by ELISA. No difference was detected between wells that were incubated for 24 hours in the presence or absence of excess unlabelled competitor protein. This suggests that the rate of dissociation of FNfn10-3JCLI4 from  $\alpha v\beta 3$  is very slow (>24 hours; Figure 2b).

To examine the rate of association between  $\alpha v\beta 3$  and biotinylated 3JCLI4, biotinylated FNfn10-3JCLI4, at concentrations of 0.01, 0.02, or 0.05  $\mu$ g/ml, was allowed to bind to  $\alpha v\beta 3$ -coated wells for periods of time ranging from one minute to two hours. For all three concentrations, levels of bound FNfn10-3JCLI4 were detectable within one minute and reached saturation levels within two hours (Figure 2c). Therefore, in light of the prolonged dissociation rate revealed in Figure 2b, we can infer that FNfn10-3JLCI4 possesses a relatively rapid on-rate for binding to  $\alpha v\beta 3$ .

To test the specificity of the interaction between FNfn10-3JCLI4 and  $\alpha v\beta 3$  integrin, biotinylated FNfn10-3JCLI4 or FNfn10-WT were added to wells coated with 5  $\mu$ g/ml concentrations of different purified integrins (Figure 2d). In this assay, the detection of plate-bound FNfn10-3JCLI4 was significant only for those wells which had been coated with  $\alpha v\beta 3$ , and not for wells coated with other integrins, including  $\alpha v\beta 5$ ,  $\alpha 5\beta 1$ ,  $\alpha 1\beta 1$  and  $\alpha IIb\beta 3$ .

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*The disintegrin echistatin and FNfn10-3JCLI4, but not GRGDSPK peptide or FNfn10-WT, effectively compete with biotinylated FNfn10-3JCLI4 for  $\alpha v\beta 3$  binding.* In order to examine the relative affinity of FNfn10-3JCLI4, as compared to other  $\alpha v\beta 3$  binding molecules, a competition ELISA analysis was performed. In these experiments, biotinylated FNfn10-3JCLI4 at 800 pM was mixed with molar ratios of competitor proteins ranging from 0.01 to 100, and allowed to bind to  $\alpha v\beta 3$  coated wells (Figures 3a and 3b). Binding of biotinylated FNfn10-3JCLI4 to  $\alpha v\beta 3$  was unaffected by the presence of the linear integrin-binding peptide (GRGDSPK) or FNfn10-WT, even when these molecules were added at 100-fold molar excess (80 nM), relative to FNfn10-3JCLI4. In contrast, unlabelled FNfn10-3JCLI4 and echistatin inhibited binding of biotinylated FNfn10-3JCLI4 at roughly equimolar concentrations ( $IC_{50}$  values were 750 and 930 pM, respectively, as calculated by logarithmic curve-fit). These findings strongly suggest that FNfn10-3JCLI4 and echistatin have nearly equivalent affinities for  $\alpha v\beta 3$  and bind to the same site; echistatin has a published  $K_d$  of 330 pM(20).

*FNfn10-3JCLI4 is an effective and specific staining reagent, when used in flow cytometric analysis.* Biotinylated FNfn10-3JCLI4 (1  $\mu$ g/ml) was added to wild-type K562 cells and to K562 cells that had been stably transfected with  $\alpha v\beta 3$  integrin (generous gift of Dr. S. Blystone)(17). Surface bound FNfn10-3JCLI4 was then detected using streptavidin-APC and stained cells were enumerated by flow cytometry. The mean fluorescence intensity of staining on the  $\alpha v\beta 3$ -positive cells was approximately three logs higher than on the non-transfected control cells (Figure 4a), and concentrations of biotinylated FNfn10-3JCLI4 as low as 8ng/ml were found to be capable of effectively and specifically staining K562- $\alpha v\beta 3$  cells (data not shown).

Having optimized our staining analysis using the K562- $\alpha v\beta 3$  cells, we proceeded to a more complete analysis of the specificity of cell surface binding of biotinylated FNfn10-3JCLI4, using

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a panel of K562 cell sublines, each of which had been stably transfected with various integrin heterodimers ( $\alpha v\beta 3$ ,  $\alpha v\beta 5$ ,  $\alpha IIb\beta 3$ ,  $\alpha 4\beta 1$ , and  $\alpha 4\beta 7$ ; gift of S. Blystone)(17). These experiments revealed that FNfn10-3JCLI4 showed a strong selective preference for  $\alpha v\beta 3$ , although it did also react very weakly with  $\alpha IIb\beta 3$  positive cells. In contrast, FNfn10-WT showed a slight preference for cells expressing  $\alpha v\beta 3$ , but stained all of the K562 lines with low intensity (Figure 4b).

One of the unique properties of the FNfn10 scaffold is its high level of physical stability. We therefore examined the effect of prolonged incubation at elevated temperatures on the binding activity of FNfn10-3JCLI4, as compared to the  $\alpha v\beta 3$ s-specific monoclonal antibody, LM609. In these studies, FNfn10-3JCLI4 and LM609 were incubated for 24 hours at 4, 20, 37, 50, 65, or 75 degrees celsius, prior to addition to K562- $\alpha v\beta 3$  cells and performance of flow cytometry. As can be observed in Figure 4c, incubation of biotinylated FNfn10-3JCLI4 at 75°C for 24 hours had only a modest effect on its cell binding activity; in contrast, the same conditions resulted in the complete elimination of LM609's ability to interact with  $\alpha v\beta 3$ .

*FNfn10-3JCLI4 inhibits  $\alpha v\beta 3$ -dependent cell adhesion but not  $\alpha IIb\beta 3$ -dependent cell adhesion.* K562- $\alpha v\beta 3$  cells, but not K562 cells, adhere strongly to vitronectin (but not BSA). This property was therefore used as the basis for a quantitative assessment of the ability of FNfn10-3JLCI4 to disrupt  $\alpha v\beta 3$  dependent cell adhesion. To do this, K562- $\alpha v\beta 3$  cells were allowed to adhere to vitronectin-coated wells, and the number of bound cells per well was then quantified by crystal violet staining and cell solubilization.

LM609, a commonly used  $\alpha v\beta 3$  function-blocking antibody, and FNfn10-3JCLI4 were both found to inhibit adhesion of K562- $\alpha v\beta 3$  cells to vitronectin, while FNfn10-WT showed little effect in this assay (Figure 5a). A more careful analysis, using a wider range of protein concentrations, revealed that FNfn10-3JCLI4 inhibits  $\alpha v\beta 3$ -dependent adhesion to vitronectin at approximately

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the same concentrations as the well-characterized,  $\alpha v\beta 3$ -binding distintegrin, echistatin (Figure 5b). Based on an exponential curve-fit, echistatin was found to inhibit  $\alpha v\beta 3$ -mediated cell adhesion to vitronectin with an  $IC_{50}$  of 5.9 nM, while FNfn10-3JCLI4 inhibited  $\alpha v\beta 3$ -dependent adhesion to vitronectin with an  $IC_{50}$  of 8.6 nM ( $R>0.99$  in both cases). Finally, we also examined the effect of FNfn10-3JCLI4 on  $\alpha IIb\beta 3$ -dependent cell adhesion, because of the weak binding activity of FNfn10-3JCLI4 for K562- $\alpha IIb\beta 3$  cells that was revealed in our flow cytometric analyses. These experiments revealed that FNfn10-3JCLI4 had no measurable effect on  $\alpha IIb\beta 3$ -mediated cell adhesion to fibronectin, while echistatin inhibited  $\alpha IIb\beta 3$ -dependent adhesion with an  $IC_{50}$  of 10.2 nM ( $R>0.99$ ; Figure 5c).

## Discussion

In this work, we have applied phage display technology and random mutagenesis techniques to carry out affinity maturation of FNfn10 binding to  $\alpha v\beta 3$  integrin. Using one phage clone that was derived from a biopanning screen against immobilized  $\alpha v\beta 3$ , 3JCLI4, we found the following: (i) modified FNfn10 phage clones, including 3JCLI4, which bind to  $\alpha v\beta 3$  integrin all contain a RGDWXE consensus and exhibit calcium-dependent binding; (ii) purified FNfn10-3JCLI4 protein binds to immobilized human  $\alpha v\beta 3$  integrin with much higher affinity than FNfn10-WT and exhibits only background binding to other purified integrins; (iii) binding of FNfn10-3JLCI4 to  $\alpha v\beta 3$  could be successfully competed using approximately equimolar concentrations of unlabelled FNfn10-3JCLI4 or echistatin, but not by either FNfn10-WT or GRGDSPK peptide (even when added at 100-fold molar excess); (iv) FNfn10-3JCLI4 is a sensitive and specific reagent for the detection of human  $\alpha v\beta 3$  integrin in flow cytometry applications; (v) the binding of FNfn10-3JCLI4 to  $\alpha v\beta 3$  integrin is maintained even after prolonged exposure of FNfn10-3JCLI4 to high temperature, and (vi) FNfn10-3JCLI4 inhibits cell adhesion via  $\alpha v\beta 3$  but not  $\alpha IIb\beta 3$  integrin, at nanomolar concentrations.

The RGDW consensus sequence that was detected in our  $\alpha v\beta 3$ -selected FNfn10-display phage clones has previously been reported to be preferentially selective for  $\alpha IIb\beta 3$  integrin over  $\alpha v\beta 3$ , at least in the context of disintegrins such as eristostatin(21). RGDW peptides are also used to induce integrin activation and in competition assays with putative  $\alpha IIb\beta 3$  integrin ligands(22). Because FNfn10-3JCLI4 exhibits no binding to plate-immobilized  $\alpha IIb\beta 3$  and very low cross-reactivity with  $\alpha IIb\beta 3$ -positive cells in flow cytometric analysis, the tertiary structure of FNfn10 may play a role in the increased specificity of this RGDW-containing molecule for  $\alpha v\beta 3$ .

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integrin. Alternatively, the glutamic acid residue within the extended consensus motif (RGDWXE) may be significant. The disintegrins eristostatin and EC6B each contain an aspartic acid residue at the corresponding location (RGDWND)(21,23,24), and though they both bind  $\alpha v\beta 3$ , they interact preferentially with  $\alpha IIb\beta 3$ . It will be interesting to characterize the three-dimensional structure and conformational dynamics of the FNfn10 mutants obtained in this study.

Like the disintegrins, FNfn10-3JCLI4 is a small monomeric molecule with high integrin-binding affinity. In our studies, echistatin and FNfn10-3JCLI4 were inferred to have similar binding affinities for  $\alpha v\beta 3$  because they were both able to compete with biotinylated FNfn10-3JCLI4 for binding to immobilized  $\alpha v\beta 3$ , at roughly equimolar concentrations. Consistent with this, echistatin has a reported  $K_d$  of 330 pM for  $\alpha v\beta 3$ (20)while the value calculated here for the half-maximal binding affinity of FNfn10-3JCLI4 for  $\alpha v\beta 3$  was 800 pM.

Biochemical analyses revealed a rapid rate of association rate between FNfn10-3JCLI4 and  $\alpha v\beta 3$  (minutes), and a very slow rate of dissociation (> 24 hours). These properties, combined with its high affinity for  $\alpha v\beta 3$ , suggested to us that FNfn10-3JCLI4 might be suitable for use in flow cytometric applications. Experimental analysis revealed this was indeed the case, and these studies also showed that FNfn10-3JCLI4 performed with similar specificity to an  $\alpha v\beta 3$ -specific monoclonal antibody in flow cytometric staining using K562- $\alpha v\beta 3$  cells. It should be noted that FNfn10-3JCLI4 is monomeric, unlike monoclonal antibodies (divalent) or other cell-staining reagents used in flow cytometry (MHC:peptide tetramers). Furthermore, FNfn10-3JCLI4 is considerably more heat stable than a typical monoclonal antibody, as revealed by its ability to continue to bind  $\alpha v\beta 3$ , even after 24 hr. incubation at 75°C.

A problem encountered in many molecules that target  $\alpha v\beta 3$  integrins is their cross-reactivity with other integrin subtypes, particularly other  $\alpha v$  or  $\beta 3$  integrins. FNfn10-3JCLI4 was found to

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bind only to immobilized purified  $\alpha v\beta 3$ , and not to other integrins tested. The failure of FNfn10-WT and FNfn10-3JCLI4 to interact with  $\alpha 5\beta 1$  is consistent with previous reports that the ninth and eighth fibronectin type III domains are also required for FNfn10 binding to  $\alpha 5\beta 1$ (25). In addition, the inability of FNfn10-3JCLI4 to bind to  $\alpha v\beta 5$  and  $\alpha IIb\beta 3$  suggests that its integrin-binding activity is likely dependent on a structural interaction with the  $\alpha v\beta 3$  complex and not with either subunit alone. The narrow integrin-binding specificity of FNfn10-3JCLI4 can be contrasted with the more broad integrin-binding profile that is exhibited by disintegrins such as eristostatin and kistrin, which bind to both  $\alpha IIb\beta 3$  and  $\alpha v\beta 3$ (21). Similarly, the penton base protein from adenovirus type 5 binds to both  $\alpha v\beta 3$  and  $\alpha v\beta 5$ , and even an engineered Fab construct (WOW-1) has been shown to exhibit cross-reactivity with  $\alpha v\beta 5$  integrin(26).

FNfn10-3JCLI4 did exhibit a weak interaction with  $\alpha IIb\beta 3$  in our flow cytometry assay, but we do not anticipate that this will be a major detriment to the more widespread use of this molecule in cell staining applications because (i) no interaction with  $\alpha IIb\beta 3$  was detected in biochemical binding studies (see above), (ii) binding to  $\alpha IIb\beta 3$  positive cells was almost 10-fold weaker than binding to  $\alpha v\beta 3$ -positive cells in the flow cytometric analysis, and (iii)  $\alpha IIb\beta 3$  expression is limited to platelets. The ability of FNfn10-3JCLI4 to block  $\alpha v\beta 3$ -dependent cell adhesion but not  $\alpha IIb\beta 3$ -mediated cell binding further supports its specificity for  $\alpha v\beta 3$ .

The structure of FNfn10-3JCLI4 is advantageous for multiple applications; FNfn10-3JCLI4 lacks disulfide bonds rendering it resistant against reducing agents, is very stable even at high temperature, and can be produced in a bacterial expression system with yields of up to 50-100 mg per liter of culture. As an endogenous human protein, wild-type fibronectin does not elicit an immune response and it is anticipated that FNfn10-3JCLI4 is likely to be similarly non-immunogenic. Furthermore, because FNfn10-3JCLI4 is a monomer that lacks disulfide bonds, it has several advantages over a monoclonal antibody with similar affinity. As a small, single-chain

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molecule, FNfn10-3JCLI4 could potentially be incorporated into gene delivery vectors (e.g. viral vectors, liposomes) for cell or tissue-specific gene expression. Indeed, the incorporation of low-affinity RGD peptides into various viral vectors, and the addition of bispecific antibody complexes to viral surface components, have already been shown to result in desirable improvements in vector specificity and transduction efficiency(27-30).  $\alpha v\beta 3$ -positive cells that may be of particular interest for targeted vector systems include dendritic cells (for vaccine applications) as well as osteoclasts and angiogenic vessels. Finally, FNfn10-3JCLI4 may have utility as a cancer imaging agent, because of its ability to recognize  $\alpha v\beta 3$  on tumor vasculature. Further studies will be required to explore these various applications.

### Acknowledgements

We thank Dr. Scott Blystone for providing us with integrin-transfected K562 cells, and Drs. Baek Kim, Jean Bidlack and Denise Hocking for helpful discussions and valuable input. We also thank Dr. Angrey Kang (The Scripps Research Institute) for providing the JC-M13-88 vectors and Dr. Sachdev Sidhu (Genentech) for advice on library construction

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**Figure Legends**

**Figure 1. Phage display screening of JCFN-RGD library.** M13 Phage displaying a library of FNfn10 clones with partially randomized FG loops (XRGDXXXX) were amplified using 0.0, 0.1, or 1 mM IPTG to vary FNfn10 copy number on the phage. Amplified phage populations were subjected to three rounds of biopanning against wells coated with  $\alpha v\beta 3$  integrin (5  $\mu$ g/ml). (a) A schematic drawing of FNfn10 (14) showing the RGD sequence and the positions of residues in the FG loop that were diversified in the JCFNRGD library. The figure was made with the program MOLSCRIPT(31). (b) Five clones each were sequenced from the second round eluate of the library amplified with 1mM IPTG (2JCAV1-2JCAV5), from the third round eluate of the library amplified with 1 mM IPTG (3JCAV1-5), from the third round eluate of the library amplified with low IPTG (3JCLI1-5), and from the third round eluate of the library amplified with no IPTG (3JCNI1-5). (c) Phage binding assay of the phage clones containing the WXE consensus and unmodified FNfn10 (pVIII-FNfn10), all amplified without IPTG. Phage inputs of  $10^9$ ,  $10^8$ , or  $10^7$  pfu were added to wells coated with 5  $\mu$ g/ml  $\alpha v\beta 3$  (solid bars) or 0.5mg/ml BSA (patterned bars). After one hour, non-binding phage were removed by extensive rinsing and bound phage were eluted with 0.2M glycine, pH 2.2. Eluates from each well were titered. Results shown are representative of three different experiments that yielded similar results.

**Figure 2. Assessment of FNfn10-3JCLI4 binding affinity to  $\alpha v\beta 3$  integrin by ELISA.** (a) To determine the half-maximal binding concentration of biotinylated FNfn10-3JCLI4 versus biotinylated FNfn10-WT, wells of a 96-well plate were coated  $\alpha v\beta 3$  (5  $\mu$ g/ml),  $\alpha 1\beta 1$  (5  $\mu$ g/ml), or BSA (0.5 mg/ml) and blocked with BSA. Biotinylated FNfn10-3JCLI4 and FNfn10-WT were then

### Fibronectin type III domain with enhanced binding to $\alpha v\beta 3$

added to the wells and allowed to bind for two hours. Bound protein was detected by streptavidin-horseradish peroxidase (2  $\mu$ g/ml) and ABTS substrate. O.D. <sub>400</sub> measurements were recorded for biotinylated FNfn10-3JCLI4 binding to  $\alpha v\beta 3$  ( $\diamond$ ), to  $\alpha 1\beta 1$  ( $\blacklozenge$ ), or to BSA (X) and biotinylated FNfn10-WT binding to  $\alpha v\beta 3$  (□). Error bars reflect the standard deviation between triplicate wells. (b) To examine protein dissociation over a prolonged (24 hour) time period, a 96-well plate was coated with 5  $\mu$ g/ml  $\alpha v\beta 3$  integrin and then incubated with 0.02  $\mu$ g/ml biotinylated FNfn10-3JCLI4 for two hours; as a control, 10 mM EDTA was added to certain wells, in order to calculate the background level of FNfn10-3JCLI4 binding. After rinsing, 2  $\mu$ g/ml unlabelled FNfn10-3JCLI4 was added to the preformed protein complexes present in the wells 24, 14, 4, 2 and 1 hours prior to detection of remaining plate-bound biotinylated FNfn10-3JCLI4 using streptavidin-horseradish peroxidase and ABTS. Baseline binding activity (100%) was calculated as the amount of biotinylated FNfn10-3JCLI4 which remained bound to the plate following incubation of the well for 24 hours, in the presence of buffer alone (i.e., in the absence of any competitor protein), and the O.D. <sub>400</sub> of FNfn10-3JCLI4 bound in the presence of 10 mM EDTA was subtracted as background. All incubations with competitor (background-subtracted) are expressed as a percentage of the O.D. <sub>400</sub> of baseline binding (background-subtracted). Error bars reflect the standard deviation between triplicate wells. (c) To examine rate of association of  $\alpha v\beta 3$  and biotinylated FNfn10-3JCLI4, a 96-well plate coated with 5  $\mu$ g/ml  $\alpha v\beta 3$  integrin was blocked with BSA. 0.01 (▲), 0.02 (■), or 0.05 (◆)  $\mu$ g/ml of biotinylated FNfn10-3JCLI4 was then added to the coated wells, at 240, 30, 10, 3, and 1 minute prior to washing and detection. After detection with streptavidin-horseradish peroxidase/ABTS, the O.D. <sub>400</sub> of the plate was recorded. Error bars reflect the standard deviation between triplicate wells. (d) A 96-well plate was coated with  $\alpha v\beta 3$ ,  $\alpha v\beta 5$ ,  $\alpha IIb\beta 3$ ,  $\alpha 1\beta 1$ , and  $\alpha 5\beta 1$  purified integrins, all at 5  $\mu$ g/ml. Biotinylated FNfn10-3JCLI4 (dark bars) or FNfn10-WT (light bars) was then added at a concentration of 0.01  $\mu$ g/ml,

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and allowed to incubate for 2 hours, followed by washing and detection. Error bars reflect the standard deviation between triplicate wells. (a-d): the experiments shown are all representative of three different experiments that yielded similar results.

**Figure 3. Competition ELISAs to determine relative affinities of FNfn10-3JCLI4, echistatin, FNfn10-WT, and GRGDSPK peptide.** A BSA-blocked 96-well plate was coated with  $\alpha v\beta 3$  at 5  $\mu\text{g/ml}$ , and biotinylated FNfn10-3JCLI4 was then added in the presence or absence of a 0.01, 0.1, 1, 10, or 100-fold molar excess of unlabelled competitor protein, and incubated for two hours. After washing and detection, the O.D. <sub>400</sub> of the plate was recorded. Error bars reflect the standard deviation between triplicate wells, and the results shown are representative of three different experiments that yielded similar results. A background subtraction was performed on all data points, by subtracting the measured O.D. <sub>400</sub> value that corresponded to binding of biotinylated FNfn10-3JCLI4 in the presence of 10 mM EDTA. All values in the figure are expressed as a percentage of the O.D. <sub>400</sub> of biotinylated FNfn10-3JCLI4 binding in the absence of competitor. (a) Binding competition with unlabelled FNfn10-3JCLI4 (◆) or unlabelled FNfn10-WT (■). (b) Binding competition with unlabelled FNfn10-3JCLI4 (▲), echistatin (■), and GRGDSPK peptide (◆).

**Figure 4. Fluorescence activated cell sorting (FACS) analysis of FNfn10-3JCLI4 binding to human cells.** Biotinylated FNfn10-3JCLI4 or FNfn10-WT were added to  $10^5$  cells at a concentration of 1  $\mu\text{g/ml}$  and incubated for 30 minutes. Bound proteins were then detected with streptavidin-APC, and the mean fluorescence of ten thousand cells per sample was recorded. All experiments were performed three times, with similar results; error bars (b, c) represent the standard deviation of three samples of  $10^5$  cells stained separately. (a) Histogram plot of flow

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cytometric staining analysis of K562 and K562- $\alpha v\beta 3$  cells using FNfn10-3JCLI4. (b) Mean APC fluorescence for integrin-transfected K562 cells stained with biotinylated FNfn10-3JCLI4 (dark bars) or FNfn10-WT (light bars). (c) To determine the effect of high temperature on FNfn10-3JCLI4 stability, 1  $\mu$ g /ml 3JCLI4 (◆) or 5  $\mu$ g /ml LM609 (■) were incubated for 24 hours in FACS buffer at 4, 20, 37, 50, 65, or 75°C.  $10^5$  K562- $\alpha v\beta 3$  cells were pelleted for each sample and resuspended in the appropriately treated FNfn10-3JCLI4 or LM609, followed by detection as above.

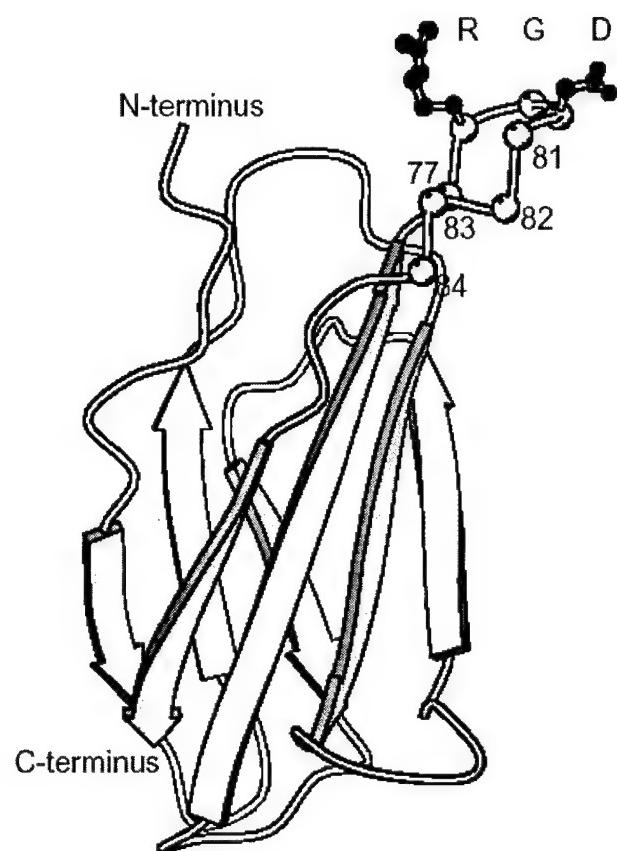
**Figure 5. Inhibition of integrin-dependent cell adhesion.** Vitronectin (a) or fibronectin (b, c) coated strips (as well as uncoated control wells) were blocked with BSA and incubated with  $10^5$  K562 cells, K562- $\alpha v\beta 3$  cells, or K562- $\alpha IIb\beta 3$  cells for two hours in the presence or absence of the indicated inhibitors. Non-adherent cells were removed by washing, while adherent cells were stained with crystal violet, solubilized, and quantitated by measuring the O.D. <sub>570</sub>. The background level of crystal violet in control wells was calculated on the basis of measured O.D. <sub>570</sub> for BSA-coated wells (no integrin). Error bars represent the standard deviation of triplicate wells, and all experiments were performed three times, with similar results. (a) Adhesion of binding of K562- $\alpha v\beta 3$  cells to vitronectin. Inhibitors added include FNfn10-3JCLI4, FNfn10-WT, and LM609 antibody, at the stated final concentrations. The lane marked “no  $\alpha v\beta 3$ ” corresponds to control K562 cells (no  $\alpha v\beta 3$ ), while “no VN” denotes cell adherence (K562- $\alpha v\beta 3$  cells) measured on control wells (no vitronectin); the lane marked “NT” corresponds to K562- $\alpha v\beta 3$  cells which were bound to vitronectin in the absence of any competitor. (b) Adhesion of K562- $\alpha v\beta 3$  cells to vitronectin. Echistatin (■) and FNfn10-3JCLI4 (◆) were added at final concentrations of 400, 40, and 4 nM, prior to addition of the cells and initiation of the binding assay. Binding is expressed as a percentage of the O.D. <sub>570</sub> recorded for K562- $\alpha v\beta 3$  adhesion in

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the absence of competitor, and a background subtraction was performed for all data points, which corresponded to the measured O.D. <sub>570</sub> for BSA-coated wells (no integrin). (c) Adhesion of K562- $\alpha IIb\beta 3$  cells to fibronectin. Echistatin (■) and FNfn10-3JCLI4 (◆) were added at final concentrations of 400, 40, and 4 nM prior to addition of the cells and initiation of the binding assay. Binding is expressed as a percentage of the O.D. <sub>570</sub> recorded for K562- $\alpha IIb\beta 3$  adhesion in the absence of competitor, and a background subtraction was performed for all data points, which corresponded to the measured O.D. <sub>570</sub> for BSA-coated wells (no integrin).

Fibronectin type III domain with enhanced binding to  $\alpha v \beta 3$

Figure 1a:



### Fibronectin type III domain with enhanced binding to $\alpha v\beta 3$

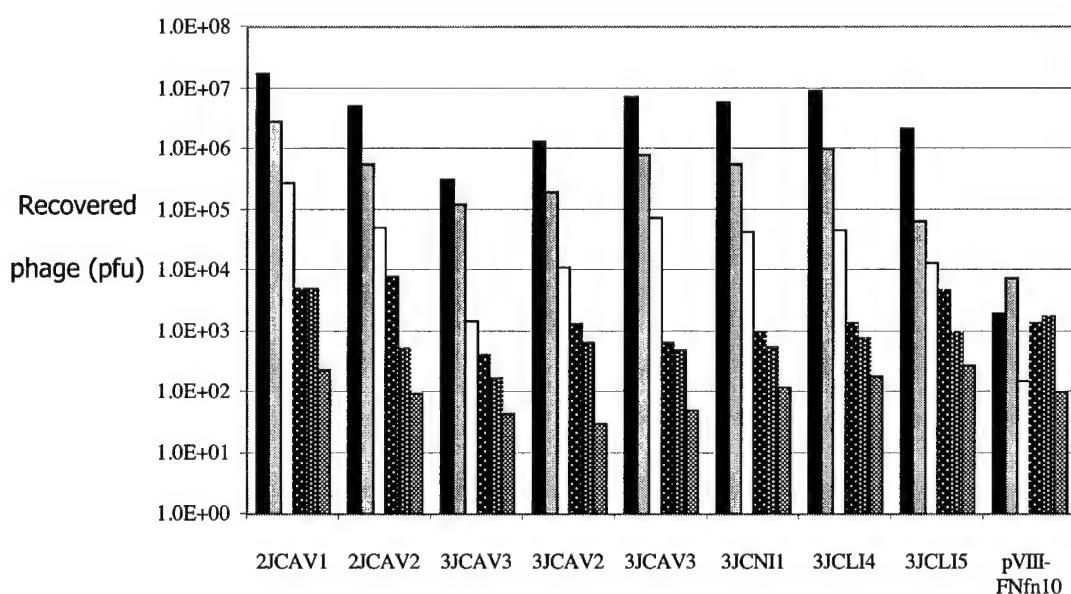
Figure 1b:

<b>2JCAV1:</b> LRGDWSED	<b>3JCNI1:</b> PRGDWIEF
<b>2JCAV2:</b> VRGDWY <del>E</del> Y	<b>3JCNI2:</b> GRGDSPAS
<b>2JCAV3:</b> VRGDCSSS	<b>3JCNI3:</b> GRGDDDRLL
<b>2JCAV4:</b> GRGDLCDF	<b>3JCNI4:</b> GRGDYVLG
<b>2JCAV5:</b> GRGDSPAS	<b>3JCNI5:</b> GRGDFSL
<b>3JCAV1:</b> GRGDWTEH	<b>3JCLI1:</b> SRGDVVPP
<b>3JCAV2:</b> ARGDWVEG	<b>3JCLI2:</b> TRGDPPPH
<b>3JCAV3:</b> PRGDWTEG	<b>3JCLI3:</b> SRGDVVPP
<b>3JCAV4:</b> GRGDAFSL	<b>3JCLI4:</b> GRGDWNEG
<b>3JCAV5:</b> FRGDSPLD	<b>3JCLI5:</b> FRGDWIEL

Wild-type FNfn10:

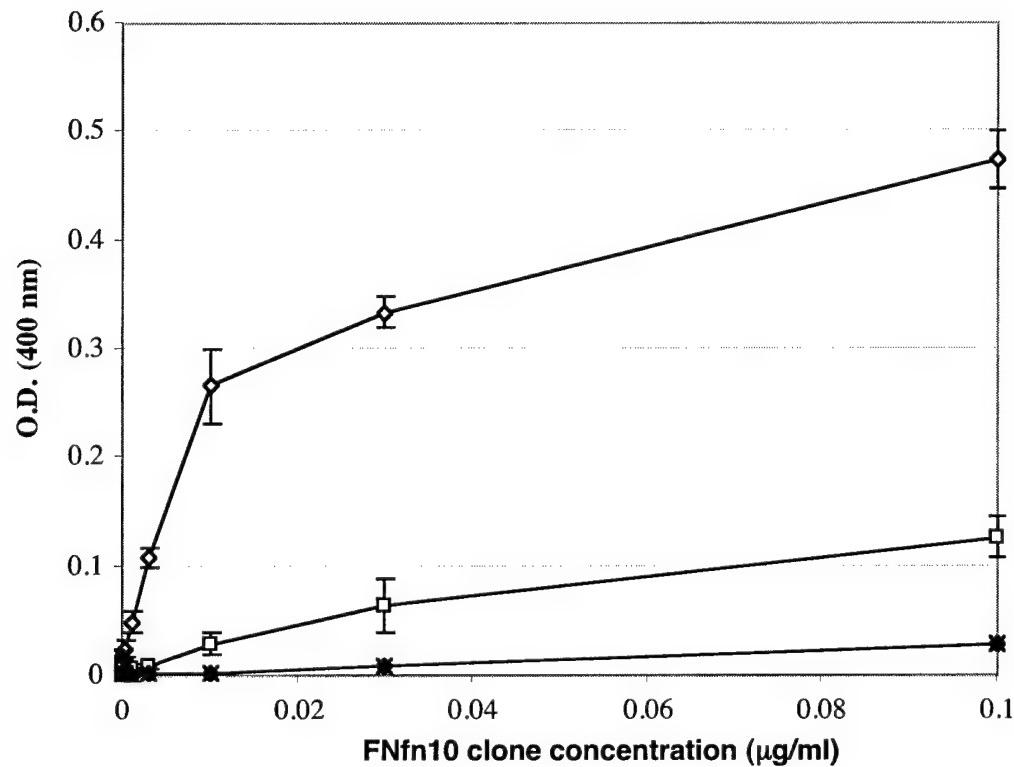
GRGDSPAS

Figure 1c:



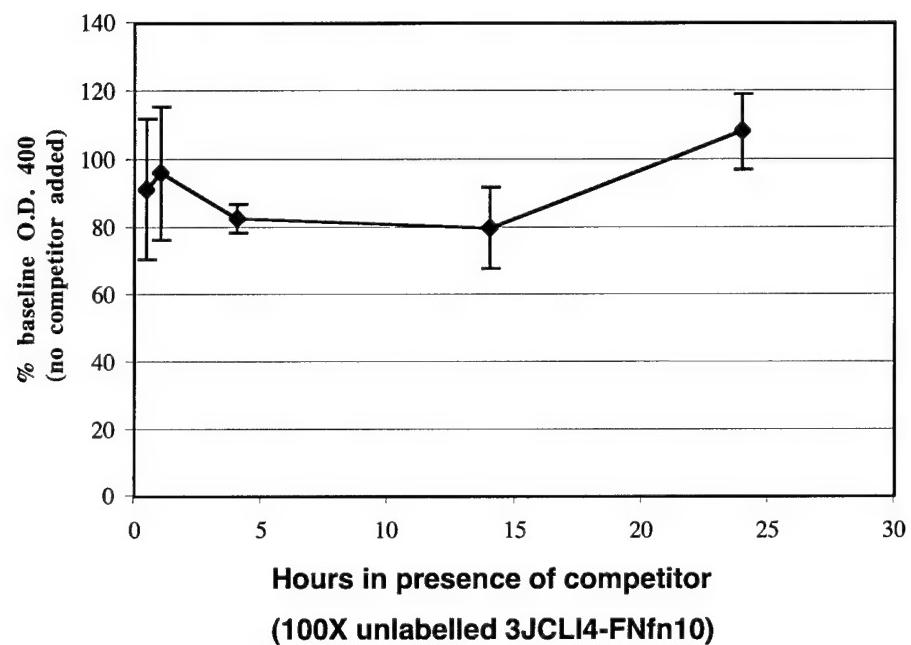
Fibronectin type III domain with enhanced binding to  $\alpha v\beta 3$

Figure 2a:



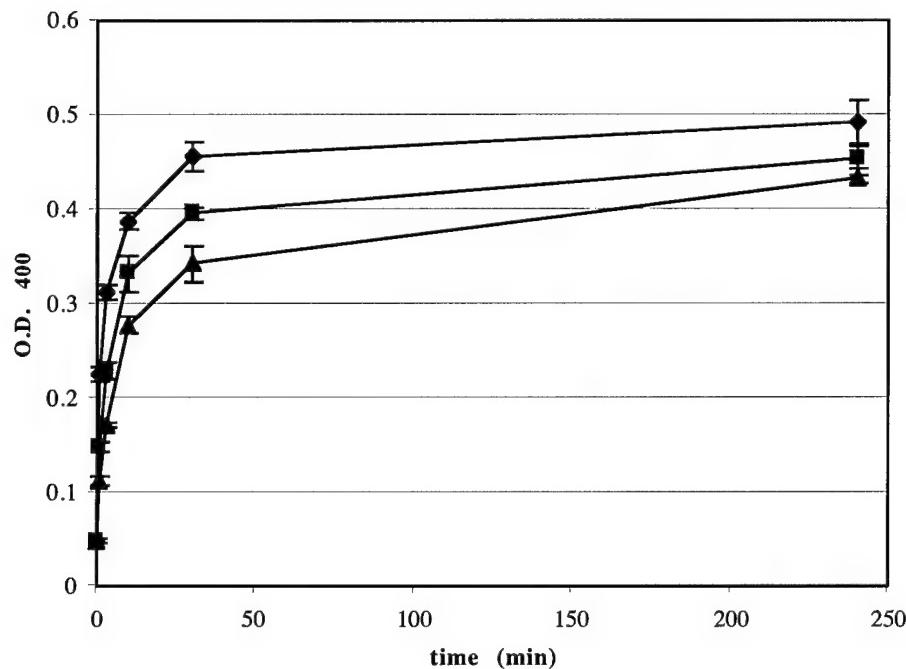
Fibronectin type III domain with enhanced binding to  $\alpha v\beta 3$

Figure 2b:



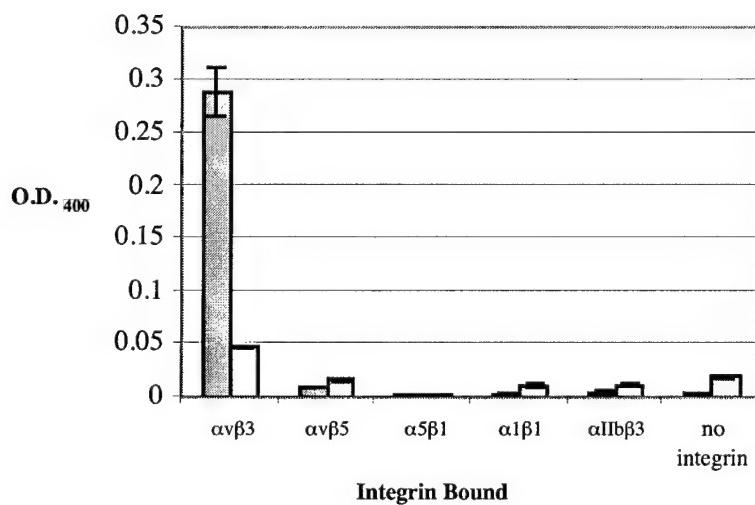
Fibronectin type III domain with enhanced binding to  $\alpha v\beta 3$

Figure 2c:



Fibronectin type III domain with enhanced binding to  $\alpha v \beta 3$

Figure 2d:



Fibronectin type III domain with enhanced binding to  $\alpha v\beta 3$

Figure 3a:

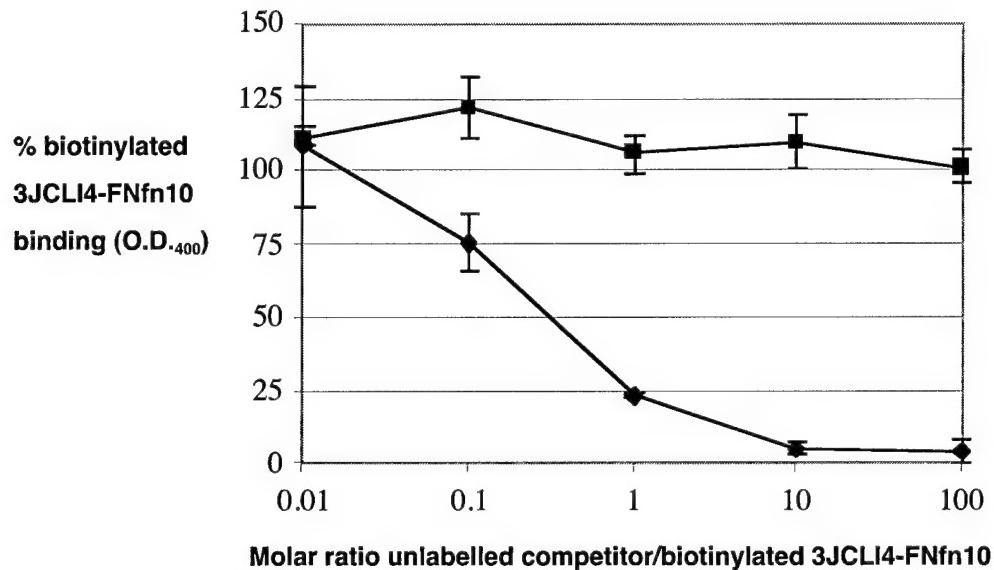
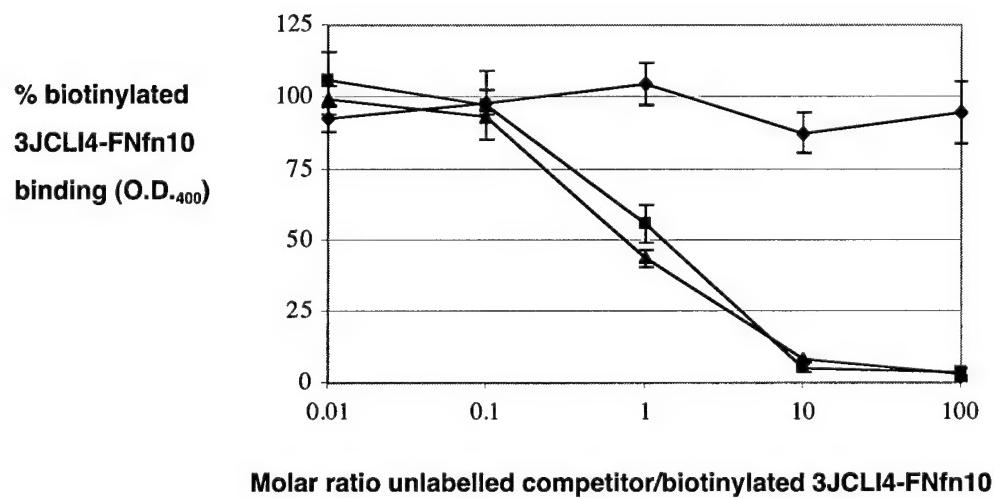
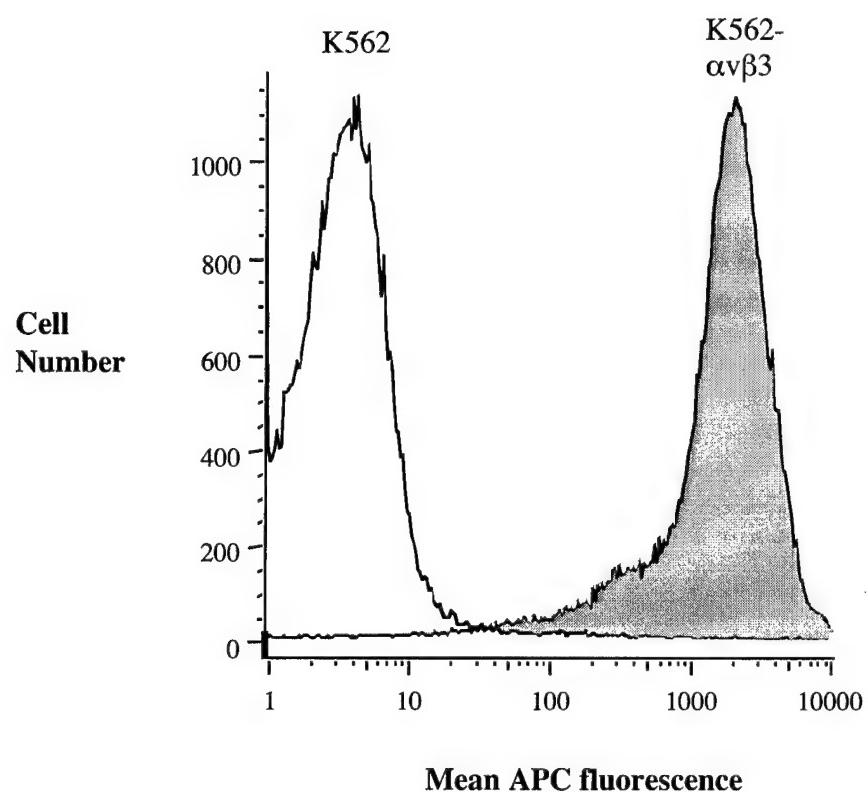


Figure 3b:



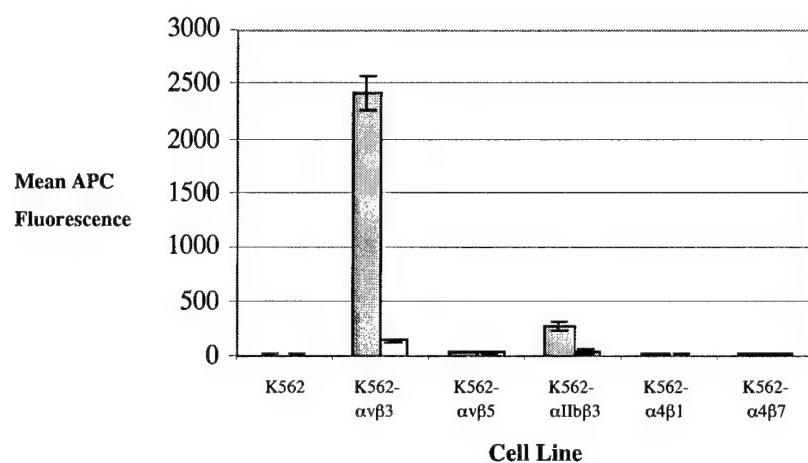
Fibronectin type III domain with enhanced binding to  $\alpha v\beta 3$

Figure 4a:



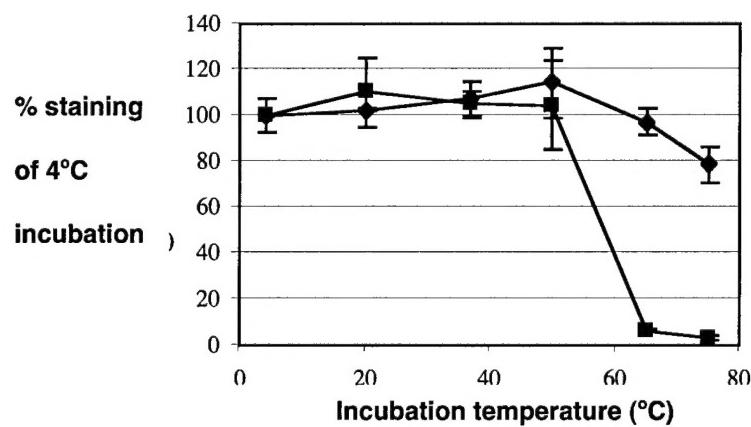
Fibronectin type III domain with enhanced binding to  $\alpha v\beta 3$

Figure 4b:



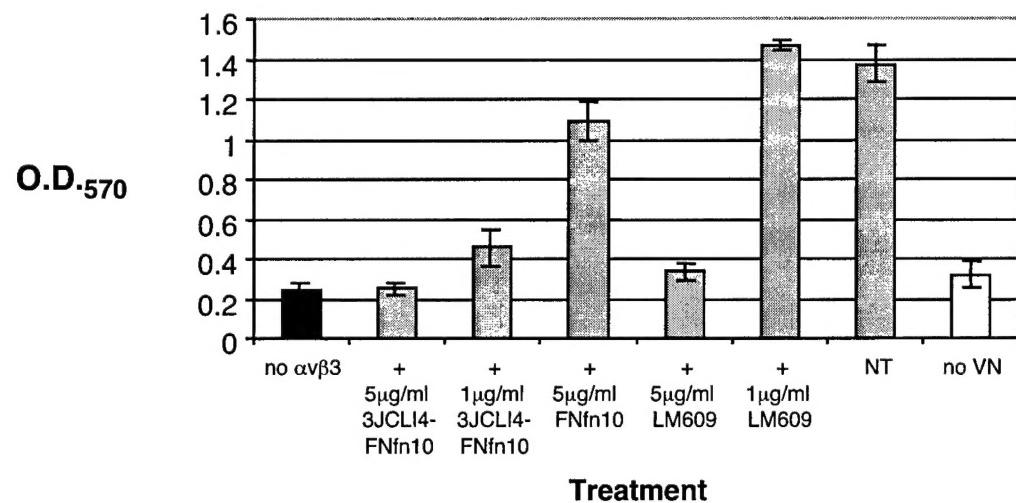
Fibronectin type III domain with enhanced binding to  $\alpha v\beta 3$

Figure 4c:



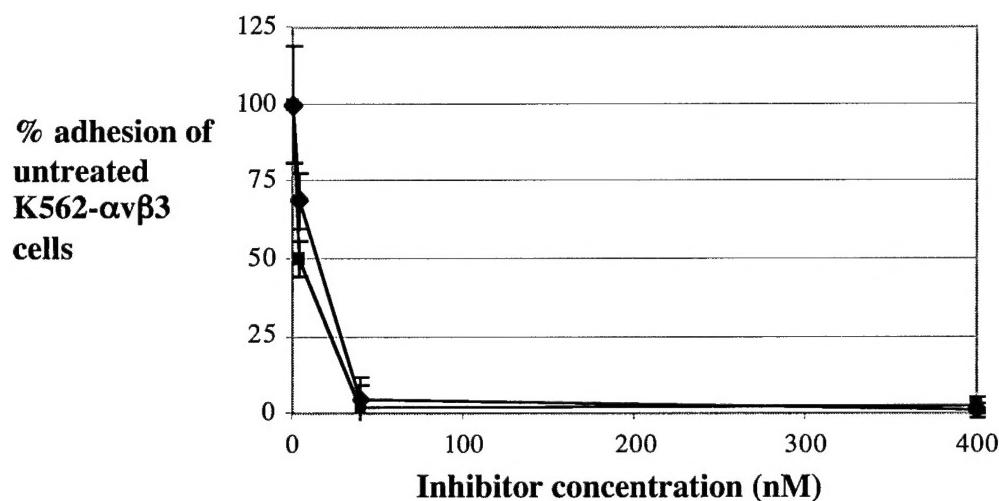
Fibronectin type III domain with enhanced binding to  $\alpha v\beta 3$

Figure 5a:



## Fibronectin type III domain with enhanced binding to $\alpha\beta_3$

Figure 5b:



Fibronectin type III domain with enhanced binding to  $\alpha v\beta 3$

Figure 5c:

